Space propulsion system profiles

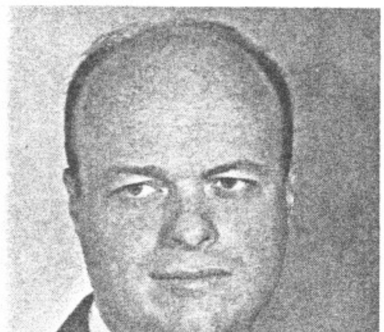
Schemes for such systems are many and diverse, yet all seem to deserve consideration . . . Better power efficiency appears to be the real challenge in propulsion system design

By William R. Corliss

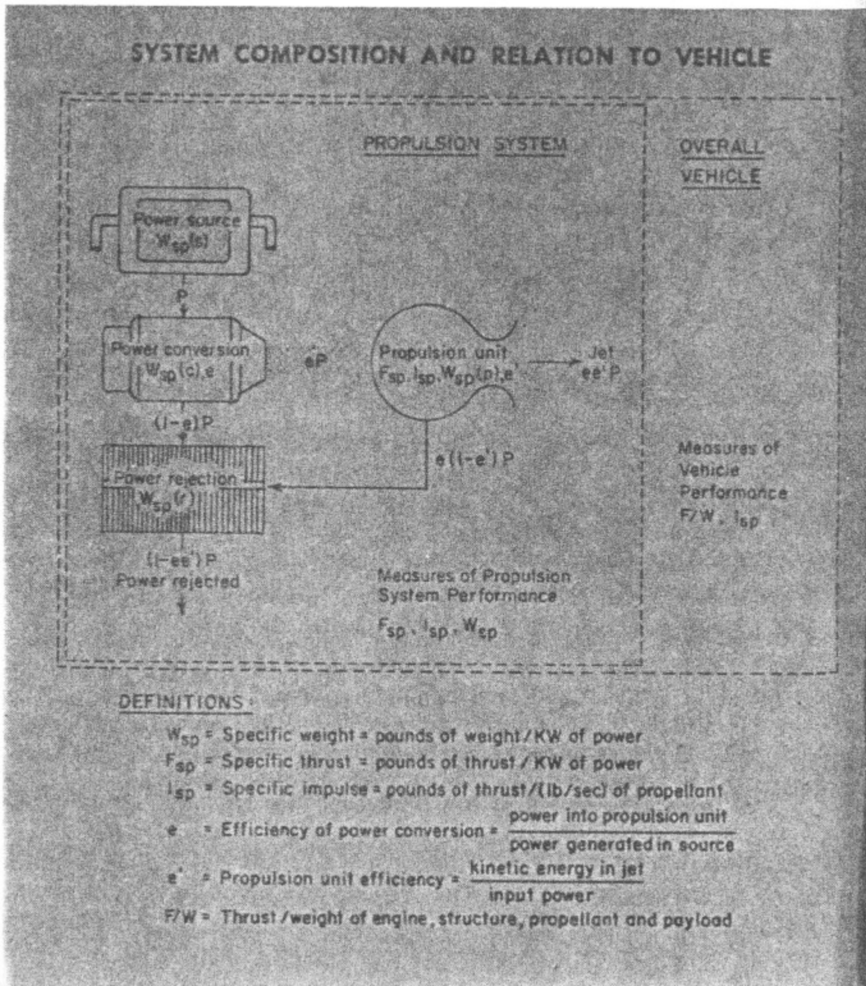
GENERAL ELECTRIC CO., CINCINNATI, OHIO

LIKE any other engine, the space propulsion system is only part of a larger entity—spaceship, satellite, or probe. The propulsion system provides its vehicle with appropriate thrust and specific impulse to perform an assigned mission satisfactorily. Vehicle performance may be expressed by thrust/weight ratio, which defines the acceleration limit of the vehicle, and specific impulse, which indicates the propulsion unit's propellant economy.

But the performance of a space propulsion system cannot be described completely by numbers. Performance may also be said to include many nonnumerical factors, the most important of which are:



William R. Corliss is a space systems specialist at GE's Flight Propulsion Lab Dept. He received a B.S. in physics from Rensselaer Polytechnic Institute in 1950, and an M.S. in physics from the Univ. of Colorado in 1953, the intervening time seeing him also employed by the Univ. of California Radiation Lab and the Central Radio Propagation Lab of the Bureau of Standards. Before joining GE in 1956, he worked on the Aircraft Nuclear Propulsion Project at Pratt and Whitney.



Reliability—Probability that equipment will function satisfactorily throughout the mission.

Vulnerability—Probability that the system will not survive in the space environment during the mission.

State of the art—When the system will be operational.

Growth potential—How much the system can be improved both in performance and the ability to do new jobs.

Development risk—Proportional to the probability of encountering insoluble development problems.

The figure on the opposite page shows the composition of the space propulsion system. There must be an energy source, energy conversion equipment, a waste-heat rejector, and the propulsion unit itself. Power originates in the source and flows to the other components as indicated. To describe adequately the four separate components of the propulsion system, it is necessary first to evolve factors directly related to those which describe the performance of the vehicle. The figure also gives these measures and defines them.

Mission requirements determine the size and constituents of both the space vehicle and its associated propulsion system. For simplicity, the variables describing the mission should be closely related to the performance factors which give the capabilities of the vehicle. For most space missions, it is possible to estimate minimum performance requirements in terms of the same parameters used to describe vehicle performance—thrust/weight ratio and specific impulse. Direct comparisons between mission and vehicle are thus possible.

Three Classes of Space Mission

There are three broad classes of space missions, which the table on page 26 describes. Estimates of the minimum performance required by these mission classes are given in the figure at top right. Obviously, all missions are best accomplished by a propulsion system with high thrust/weight ratio and high specific impulse. Such an "ideal" propulsion system, of course, does not exist.

Using the coordinates in the top figure right, we can plot the calculated capabilities of some presently conceived space propulsion systems, which is done in the bottom figure on this page. Although nominal allowances are made for payload, propellant, and structural weights, the regions outlined in the F/W-I_{sp} plane should be regarded as approximate only. Still, an assessment of the propulsion systems and their possible applications may be obtained by superimposing the top and bottom figures on this page.

The bottom figure on this page shows that there

[redacted]

is a large gap between the nuclear and chemical rockets and the more advanced space propulsion concepts. This gap occurs because two basically different kinds of reaction engines are represented. Chemical and nuclear rockets accelerate mass to exhaust velocity by combustion or nuclear heat-addition and subsequent expansion through a nozzle. These systems are extremely light and fairly efficient but have low specific impulses. On the other hand, electrical engines depend on high-grade electrical energy for the electrostatic or electromagnetic acceleration of mass. The generation of this electrical power requires heavy equipment, which may have low conversion efficiency. Heavy generating equipment significantly reduces the thrust/weight ratio of electrical space engines.

There is also a falling off of thrust/weight ratio with specific impulse. The basic equations involved are shown below. The inverse proportionality of F/W_p and I_{sp} does not include the contribution of payload, propellant, and over-all structure. It does, however, serve to focus attention on the rapidly increasing power demanded by high specific impulse machines. When power is proportional to power supply weight, the F/W_p ratio suffers from the increased sizes of source and conversion equipment and the larger heat radiators required.

The power supply, including fuel, is an integral part of the space propulsion system. The weight of

BASIC EQUATIONS

$$F = \frac{\dot{w}v}{g_0} \qquad P = \frac{\dot{w}v^2}{2g_0} \qquad I_{sp} = \frac{v}{g_0}$$

If $W_p \propto P$ then: $F/W_p \propto 1/I_{sp}$

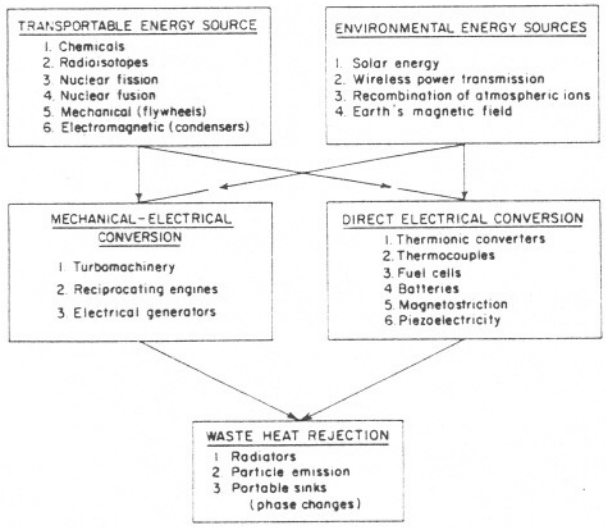
where:
- F = thrust (lb)
- v = exhaust velocity (ft/sec)
- P = power (ft-lb/sec)
- W_p = weight of propulsion system alone (lb)
- $\dot{w}$ = weight flow (lb/sec)
- g_0 = 32.2 ft/sec²
- I_{sp} = specific impulse (sec)

MISSION CLASSES

Class	Purpose	Minimum Requirements
Planetary surface	Launching satellites, probes, spaceships, ICBM's	$F/W > 1$ $I_{sp} > 100$
Satellite	Orbit changing and trimming, making up drag losses, attitude control	$F/W > 10^{-5}$ $I_{sp} > 1000$
Interplanetary-Interstellar*	Travel to the moon, planets, and stars (orbit to orbit)	$F/W > 10^{-4}$ $I_{sp} > 10{,}000$

* Minimum requirements for this class vary significantly with time allotted for the mission. Estimates are order of magnitude only.

CONSTITUENTS OF ELECTRICAL POWER SUPPLY



the power supply usually controls the denominator in the F/W ratio. A host of different power supplies are available. The figure above attempts to categorize some of them, which might be used in any combination. It is possible to plot the specific weights (pounds of weight per kilowatt of power) and efficiencies of all components, but this procedure is complicated by the fact that the specific weights of the heat sources are frequently sensitive to the mission length and the power level. Contrasting examples of these effects are gasoline engines and nuclear reactors. For survey purposes, it is more convenient to indicate the rough ranges of specific weights that are currently being calculated: Thermal systems (for rockets) show 0.05 to 0.5 lb/kw, and electrical systems (for ion drives) 5 to 50 lb/kw.

Reduce Specific Weights

Clearly much of the effort in space propulsion must be spent in reducing the high specific weights of electrical power supplies. Direct conversion and solar power do not present ready solutions to the weight problem. In contemporary direct-conversion power supplies of more than 10 kw capacity, a heat-transfer fluid must be included to convey waste heat to the radiator. In such powerplants, only the electrical generator itself will be replaced by a static part. The pump or compressor, the radiator, and the heat sources are still present. In the case of solar power, the source of specific weight must include the weight of the large collector, meteoroid shields, and supports.

It has become apparent that, with currently envisaged technology, there is no combination of power supply components that will allow over-all specific weights much below 10 lb/kw for electrical powerplants. Ten years from now, direct conversion, metal-vapor cycles, and other advanced developments will bring values as low as 5 lb/kw.

The propulsion unit is the distinctive part of the propulsion system. The power supply may be used for auxiliary power and other purposes, but the propulsion unit has only one task, to provide thrust. Its contribution to the system performance is usually through the specific thrust term (pounds of thrust per kilowatt of power) which factors in efficiency in its usual definition. The contribution to the weight of the system is usually small in comparison with the power supply. The propulsion unit also determines the specific impulse.

Space propulsion units take diverse forms. The table below gives major characteristics, typical system performances and some possible applications of seven of the more important types of propulsion unit. Note that there seem to be applications for all of the systems listed. This indicates that the spectrum of contemplated space missions is very broad and that, although some missions are definitely more important than others, there is no incontrovertible reason for eliminating any of the systems listed. It is also evident that there is no propulsion system which is "best" as yet, although there may be one system which meets the needs of a particular mission best.

The real challenges in propulsion unit design lie in the area of better power efficiency ($\acute{e}$). Since some projected efficiencies already approach 100 per cent, there is not too much room for improvement here for many systems. Reliability is a critical factor with missions being planned for several years duration. A clear opportunity for improvement lies in the design of a system with both thrust and specific impulse modulated, allowing it to perform different missions.

A review of some of the proposed space power supplies and propulsion units seems to show that progress toward the "ideal" system with high F/W and I_{sp} depends heavily on the development of lighter and more efficient power supplies, and, to a lesser extent, more efficient propulsion units. Concurrent improvements in reliability, vulnerability, and the other qualitative parameters are also desirable, particularly for long missions.

TYPICAL PROPULSION UNITS

Type	Characteristics	Barrier Problems	Typical Performance	Applications
Chemical Rockets	Converts chemical energy into exhaust kinetic energy by heating combustion gases and expanding them through a nozzle.	Limited by lack of high-temperature materials, the low energy of the chemical bond, and the high molecular weight of combustion gases.	$F/W = 2 \times 10^{0}$ $I_{sp} = 300$ sec	Planetary surface missions.
Nuclear-Fission Rocket	Converts nuclear-fission energy into exhaust kinetic energy by heating a propellant in a nuclear reactor and expanding it through a nozzle	Limited by the lack of high-temperature materials, nuclear hazards, and lack of easily stored and handled, low-molecular-weight propellants.	$F/W = 2 \times 10^{0}$ $I_{sp} = 800$ sec	Planetary surface missions.
Plasma Jet	Converts the energy in an electric arc into the kinetic energy of a propellant which forms a constricting vortex about the arc. The fluid vortex cools the engine structure and confines the arc, allowing temperatures approaching 100,000 F to be reached.	Erosion of nozzle and orifice by hot propellant. The lack of easily handled and stored, low-molecular-weight propellants.	$F/W = 10^{-3}$ $I_{sp} = 1000$ sec	Satellite missions, probes, and slow interplanetary missions.
Magnetohydrodynamic	Magnetic pressures generated by plasma currents are used to accelerate plasma.	Low efficiencies, low-weight flows.	$F/W = 10^{-4}$ $I_{sp} = 10{,}000$ sec	Satellite missions, probes, and slow interplanetary missions.
Ion Drive	Uses electrostatic fields to accelerate charged particles. Require ion source and beam neutralizer.	Space charge limitations on current source areas and space charge neutralizers; electrical breakdown across propellant in accelerator.	$F/W = 10^{-4}$ $I_{sp} = 10{,}000$ sec	Satellite missions, probes, and slow interplanetary missions.
Photon Drive	Obtains thrust from the momentum carried off by photons emitted by heated objects like filaments and radiator pipes or by nuclearly generated electromagnetic radiation.	Excessive power requirements for reasonable thrusts (7.4×10^{-7} lb/kw). Large radiating areas required.	$F/W = 10^{-6}$ $I_{sp} = 30{,}000{,}000$ sec	Probes, slow interplanetary missions.
Solar Sail	Uses light pressure to obtain thrust.	Tremendous areas needed to obtain significant thrusts (10^{-7} lb/ft^2).	$F/W = 10^{-4}$ I_{sp} = infinity	Satellite missions, probes, and slow interplanetary missions.